

Fifty Years of Quasars: Physical Insights and Potential for Cosmology

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Abstract. Last year (2013) was more or less the 50th anniversary of the discovery of quasars. It is an interesting time to review what we know (and don't know) about them both empirically and theoretically. These compact sources involving line emitting plasma show extraordinary luminosities extending to one thousand times that of our Milky Way in emitting volumes of a few solar system diameters (bolometric luminosity $\log L_{\text{bol}} \sim 44 - 48$ [erg s⁻¹]: $D=1-3$ light months $\sim 10^3 - 10^4$ gravitational radii). The advent of 8-10 meter class telescopes enables us to study them spectroscopically in ever greater detail.

In 2000 we introduced a 4D Eigenvector 1 parameters space involving optical, UV and X-ray measures designed to serve as a 4D equivalent of the 2D Hertzsprung-Russell diagram so important for depicting the diversity of stellar types and evolutionary states. This diagram has revealed a principal sequence of quasars distinguished by Eddington ratio (proportional to the accretion rate per unit mass). Thus while stellar differences are primarily driven by the mass of a star, quasar differences are apparently driven by the ratio of luminosity-to-mass.

Out of this work has emerged the concept of two quasars populations A and B separated at Eddington ratio around 0.2 which maximizes quasar multispectral differences. The mysterious 8% of quasars that are radio-loud belong to population B which are the lowest accretors with the largest black hole masses. Finally we consider the most extreme population A quasars which are the highest accretors and in some cases are among the youngest quasars. We describe how these sources might be exploited as standard candles for cosmology.

1. Introduction

Today the existence of a large quasar population is taken for granted. They are simply regarded as the hyperactive nuclei of galaxies observed across cosmic time. In 1963 the reaction was quite different. In the years immediately before the discovery, some blue stars had apparently been detected with radio telescopes. This was a surprise because stars are such weak radio emitters (thermal radio emission from the Sun was only detected around 1946 [1]). These mysterious radio stars were eventually observed spectroscopically and they showed most unusual spectra. Instead of typical stellar absorption line spectra they showed broad emission lines [2, 3]. At first the lines could not be identified but after some time it was realized that they were redshifted Balmer lines (in the first two cases $z = c\Delta\lambda/\lambda_0 = 0.16$ (3C 273) and 0.42 (3C 47)). In the latter case MgII2798 was detected – it had only been detected in the *sun* previously. In those

early years even the cosmological nature of the quasar redshift was an open question although a gravitational origin for the redshift had been ruled out [4]. If the redshift reflected velocity of recession in an expanding Universe then the quasars were extremely luminous—and small—based on emitting region sizes (a few thousand Schwarzschild radii) inferred from timescale of intensity fluctuations (weeks/months). Figure 1 shows an optical image and spectrum for 3C273.

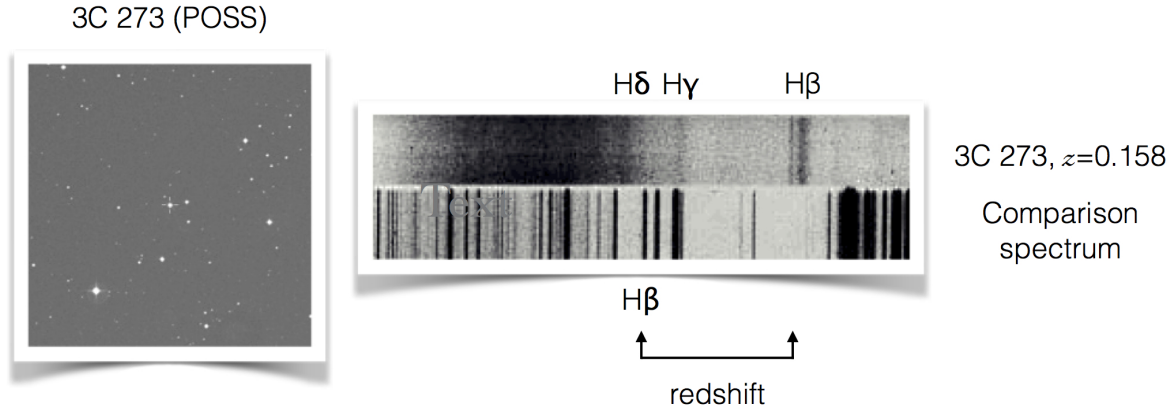


Figure 1. Left: An optical image of 3C273 the first (or one of the first) quasars discovered. It was radio-loud and also showed an optical jet. Right: optical spectrum of 3C273 showing broad Permitted and narrow forbidden emission lines. Optical FeII emission is unusually strong in this relatively nearby quasar—a harbinger of the FeII emission now seen in almost all low z quasars.

Ideas about this new constituent of the Universe were in great flux during these early years. It is important to remember that quasars were discovered 20 years before the advent of charge-coupled devices (CCD) detectors and space astronomy was in its infancy. Computers and sophisticated electronic instrumentation were yet to come. The first quasar analog spectra were recorded on glass plates (a nonlinear detector with 1-2% quantum efficiency). It is difficult from the perspective of 2014 to imagine that any progress could have been made. Already in 1967 a quasar with $z = 2.2$ was found (the record is now $z \approx 7.08$; [5]) showing broad and narrow emission lines as well as absorption lines with different redshifts [6]. This is perhaps one of the reasons why the nature of the redshift was an open question from the beginning. By about 1970 however a consensus had been reached about the nature of such sources – they were powered by gravitational accretion onto a supermassive black hole ([7, 8, 9]; the model: a line emitting accretion disk (AD) surrounding a supermassive black hole (BH): AD+BH, [10]). By 1985 an obscuring torus had been added to the standard model ([11] and references therein). A unification model involving a BH+AD+torus structure viewed from different directions can indeed unite much of the active galactic nuclei (AGN) diversity (the unifying name for all the manifestations of quasar activity “active galactic nucleus” came into use in the early ’80s). Figure 2 sketches the main elements of the standard accretion model. Not all elements are in the cartoon need to be present in the same AGN: the innermost thick structure (the slim disk) is expected to develop only for relatively high accretion rates, above Eddington ratio $\approx 0.2 - 0.3$. Some type-2 AGN may be sources accreting at very low rate, missing broad line emitting gas and not obscured by a thick torus of clumpy molecular gas [12].

2. Definition of a quasar

Physicists sometimes speak about the need for establishing an operational definition of a phenomenon in order to facilitate development of models employing the known laws of physics. In

astronomy, where sources are remote and observations beset with large uncertainties, theoretical speculations are often far ahead of the evidence. Our 1963-64 definition of quasar would involve something like "radio-loud blue variable stellar (i.e. point) source showing broad redshifted emission lines". The first quasars showed a UV excess reflecting a continuum rising toward shorter wavelengths which is well visible as the dark band short-ward of $H\delta$ on the spectrum of Figure 1. This kind of spectral energy distribution is similar to the one observed from "hot" white dwarf stars. Searches were rapidly devised to find more very blue stars. Followup spectroscopy could then separate the white dwarf stars from the high redshift quasi-stellar sources. This kind of optical selection quickly demonstrated that radio-quiet quasars outnumbered radio-loud ones. Today only a mysterious 8% of quasars with $z < 1.0$ are found to be radio-loud. "Radio" cannot be part of an operational definition for quasars; neither "blue" because quasars are now found with a wide range of colors. Note that in astronomy what you see is often affected by the intervening medium—all or part of the dispersion in a property might not be intrinsic to a source (i.e. the Sun appears redder when it is observed at low altitude).

The word "stellar" also becomes a problem for our operational definition if we realize that evidence for broad emission lines in the nuclei of some local galaxies had been known since early in the 20th century (hence the label AGN). Most notable are local spiral galaxies with ultra-luminous nuclei [13]. A conference was held at Steward Observatory in 1968 to debate the idea that Seyfert galaxy nuclei might simply be lower luminosity manifestations of the quasar phenomenon. Quasars at high redshift appear stellar because their host galaxies are too faint to be detected. Hubble Space Telescope has revealed evidence of host galaxies around many high redshift quasars. A few claims of naked quasars remain intriguing (e.g. [14]). It turns out that many quasars and Seyfert galaxies require us to remove "broad emission" from the operational definition as well because many of these sources show only narrow (forbidden) lines. Later the discovery of lineless quasars (i.e. BL Lacs) made our original definition even more off the mark [15, 16]. All or much of our problems with definition stem from the likelihood that quasars, unlike stars, are not isotropic sources. They presents different aspects when viewed at different orientations to the line of sight. Today all of the manifestations found before, during and after 1963 are united under the label "active galactic nuclei" (AGN) a term which came into usage in the early '80s. Much detailed history, and a full discussion of nomenclature, can be found in "Fifty Years of Quasars" [17].

X-ray astronomy was born with the launch of UHURU just seven years after quasars were discovered (3C273 had already been X-ray detected: [18]). The best empirical commonality (operational definition?) for AGN may involve the presence of a hard X-ray power-law component (e.g. [19]). It is important to point out that the central AD+BH+torus structure cannot be spatially resolved in any AGN even if interferometric mid-infrared observations are likely to achieve this goal [20]. Even if a few of the lowest redshift examples are eventually resolved it is not clear how much this will advance our understanding of central source structure. All is not lost of course—we can use spectroscopy to resolve the structure in many quasars—most are relatively unobscured essentially down to the BH event horizon (emission lines are seen at radii as small as a few hundred R_G in many sources—and possibly to $2 - 6 R_G$ via the 6.4keV Fe $K\alpha$ line in a few cases).

3. CONTEXTUALIZING QUASARS – TOWARDS A QUASAR H-R DIAGRAM?

Given the multiwavelength diversity of AGN properties now observed it should come as no surprise that different groups now focus on specific subtypes (e.g. blazars, radio galaxies, LINERS, narrow line Seyfert 1s) and even on observations in a particular wavelength domain. It can be educational to use the NASA Extragalactic Database (NED) search engine to identify all papers discussing one of the hundred best studied sources. In many cases one finds a strong

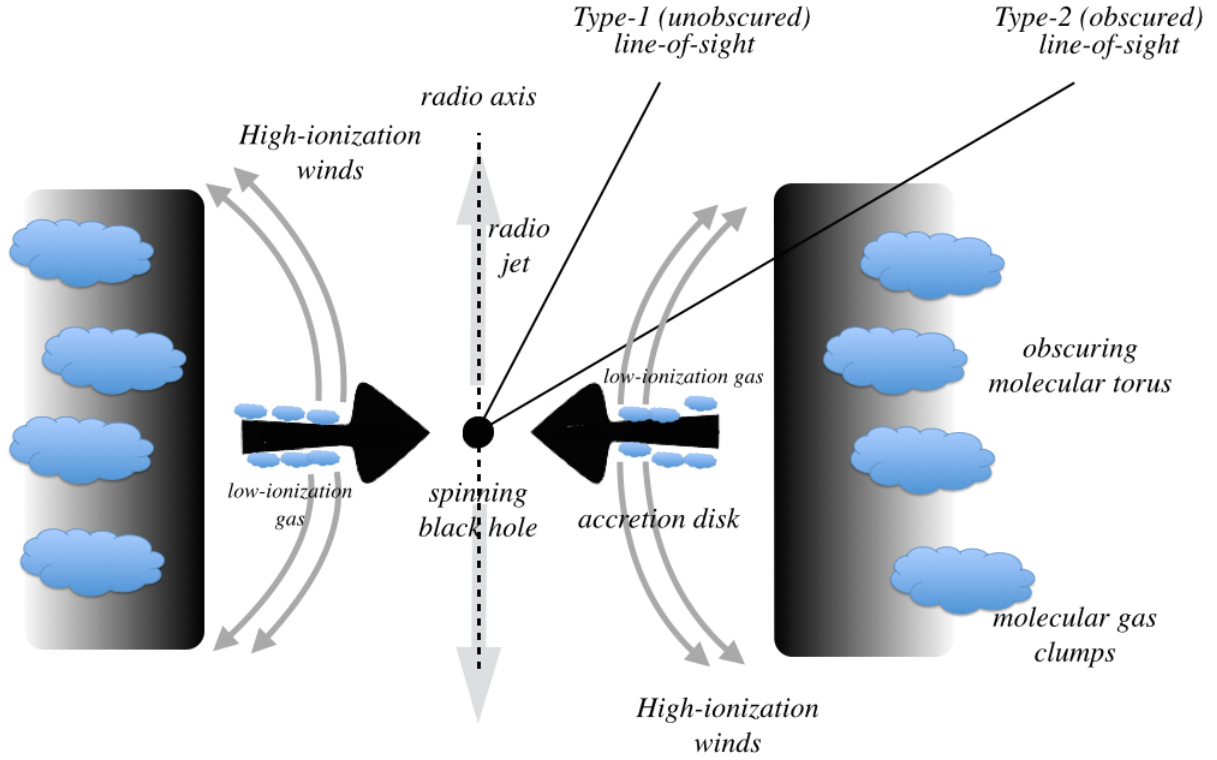


Figure 2. A cartoon illustrating AGN accretion and unification ideas. Broad lines (i.e. quasars) are seen in sources oriented at intermediate viewing angles. Narrow emission lines can be seen in all or most sources oriented near edge-on because the lower density gas extends high enough to be seen above or below the torus. The torus blocks the broad line emission from the accretion disk. The disk is shown with an “arrow” shape indicating that there are many models involving inner radiative and outer gravitational instabilities for this structure. We show a disk with an inner geometrically and optically thick structure (also known as a slim disk [21]) expected to form only for dimensionless accretion rates $\dot{m} > 0.2 - 0.3$. High ionization outflows emerge from the disk, while lower ionization gas may be confined to a flattened configuration that is coplanar with the disk (see, e.g., [22, 23] for reviews and references).

bias towards radio studies (followed by IR and X-ray) perhaps because after 50 years we are still unclear if all quasars pass through a RL phase or if the 8% of RL quasars have fundamentally different source central structure/kinematics diversity

Another important component missing from quasar studies until the '90s (or we would say the 2000s) was an empirical formalism allowing one to contextualize quasar (especially spectroscopic) diversity. When making a NED search one often finds only 1-2 out of 100-500 references for a specific source presenting/discussing optical spectra. One reason for this bias is probably the widespread impression that all quasar spectra are self similar. Nothing could be further from the truth. It is our contention that this misimpression has seriously retarded progress on quasar studies.

A good and simple example of source contextualization involves the Hertzsprung-Russell diagram for stars (Figure 3). If all stellar spectra were self similar such a contextualization would not be useful or even possible. But we recognize at least seven – OBAFGKM – principal stellar spectral types organized along a Main Sequence as well as specific regions of the diagram

occupied by stars in particular states of evolution. The principal driver is recognized to be stellar mass with different fusion processes and metallicity playing important roles as well. Can the much more energetic quasar phenomenon contain so little spectroscopic diversity that contextualization not useful? How has such an impression come about? In part it reflects the scarcity of good spectroscopic data before 1990. In 1989 only about 60 quasars could be found in the literature with spectra suitable for serious classification but even these revealed interesting diversity in line profile shape [24]. The lack of good spectra fed the impression that all quasars are spectroscopically similar (perhaps in the face of the striking broad redshifted emission lines all the rest seemed minor details). We think that the lack of clarity about quasar spectral diversity is responsible for our failure, up to the present, to develop a standard physical model for the broad line emitting region of quasars (e.g. [25]). The right panel of Figure 3 shows the principal occupation sequence for quasars in a simple plot involving two fundamental optical spectroscopic measures.

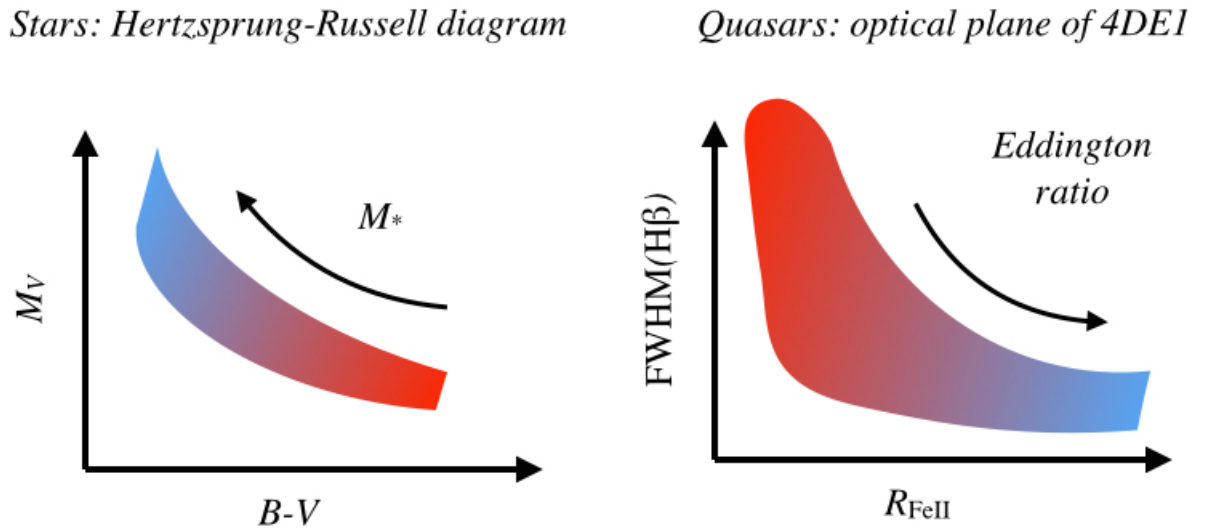


Figure 3. Cartoon representations of the 2D stellar H-R diagram (left) and 2 of the 4 dimensions (i.e. optical plane) of the 4D Eigenvector 1 (4DE1) diagram for quasars. In both cases the schematic main sequence of source occupation is shown with the stellar sequence drive by mass (M) and the quasar sequence driven by Eddington ratio. More dimensions are needed for quasars because, unlike stars, they are not isotropic radiators

Serious progress on the spectroscopic front begins after 1992 with an increase in the quantity and quality ($S/N \sim 20$; $R \sim 1000$) of quasar spectra thanks mostly to the CCD detector which entered astronomy in 1982. Lick Observatory was ahead of the game in the sense that their IDS (image dissector scanner) system gave them the competitive edge in the 1970s-80s. Most of this early work focussed on the brighter Seyfert 1 nuclei. Quasar spectroscopy had to wait for the CCD era (except for the image photon counting system (IPCS) used at Palomar in this period).

From this point onwards let us focus on type 1 AGN (quasars and Seyfert 1 galaxies) which show both high and low ionization broad emission lines. They also almost always show strong blends of permitted FeII emission—often enough that one might want to keep separate the few sources that do not show it. In this way one part of an operational definition for (low redshift) Type 1 quasars can be “broad redshifted low ionization emission lines including optical FeII”. The FeII requirement cannot be confirmed in sources beyond $z=0.7$ unless we: 1) accept UV FeII emission as a surrogate for optical FeII emission and/or 2) follow the increasingly

redshifted region of the strongest optical FeII blends near $H\beta$ into the infrared windows. This has been accomplished for about 70 quasars in the range $z=1.0-3.7$ using the VLT-ISAAC infrared spectrometer [26, 27, 28]. FeII emission is seen in all of them [28] while a study of almost 500 of the brightest low redshift quasars in the northern sky found all but 14 with detectable FeII emission [29].

Our focus on Type 1 sources reflects a working strategy that they are the high accreting **parent population** of the AGN phenomenon. Inclusion of Seyfert 1 sources with quasars requires an addition to the operational definition "stellar sources with and without evidence of a surrounding host galaxy". We assume that the broad emission lines arise in a flattened distribution of gas associated with an accretion disk (AD). The AD provides a dense medium suitable for FeII production. Permitted FeII emission is strong in most type 1 sources and its strength requires a low ionization, high density, and high column density emitting medium. The best candidate for such an emitting region is arguably the AD. There is also evidence that part of the Balmer lines arise in the clouds emitting Fe II. Gravitational accretion onto a supermassive BH is the only known mechanism that can account for the extreme luminosities of the Type 1 sources. Hence the BH+AD paradigm.

Restriction to Type 1 sources is required for this type of approach. Following everything that we know they represent the most unambiguous class of high accreting sources offering the most spectroscopic clues into their nature. Once they are fully characterized and understood one can try to unify them with other more ambiguous classes of AGN with and without broad lines. A further restriction to sources with broad emission lines AND optical FeII emission removes additional ambiguities associated with obscured sources (e.g. Seyfert 1.5) and sources with the narrowest broad lines (e.g. narrow line Seyfert 1 (NLSy1) sources). Even with these restrictions we find impressive spectroscopic diversity. Understanding this diversity –we argue– is a key to development of successful physical models for the broad line region (BLR) of Type 1 sources.

Progress in understanding Type 1 quasars came with the advent of larger samples of quasars with high s/n spectra. A major advance involved analysis of spectra for 87 sources in the Palomar Bright Quasar survey [30]. The spectra allowed accurate measurements of broad and narrow emission line properties. Principal Component Analysis (PCA) techniques were applied to the correlation matrix representing the measured parameters. This study identified the principal (Eigenvector 1) correlations that exist in the dataset and also showed that source luminosity belonged to Eigenvector 2 (the second orthogonal solution). This work (and also work on X-ray-optical correlations [31] motivated us to develop the empirical context in which to interpret the spectroscopic diversity of type 1 sources [32, 33]. Fortunately by the mid 90s the Hubble Space Telescope archive was supplying moderate quality UV spectra for more than 130 low z sources.

4. Our work with 4D eigenvector 1 – major results

We focussed our efforts on a four dimensional parameter space (4D Eigenvector 1 = 4DE1) [34]. 4DE1 has roots in the PCA analysis of the Bright Quasar Sample (87 sources, [30], hereafter BG92) as well as in correlations that emerged from ROSAT (e.g., [31]). 4DE1 as we define it involves BG92 measures: (1) full width half maximum of broad $H\beta$ (FWHM $H\beta$) and (2) equivalent width ratio of optical FeII and broad $H\beta$: $R_{Fe} = W(\text{FeII}\lambda 4570)/W(H\beta)$. We added a [31]-defined measure involving (3) the soft X-ray photon index (Γ_{soft}) and a measure of (4) CIV $\lambda 1549$ broad line profile velocity displacement at half maximum ($c(\frac{1}{2})$) to arrive at our 4DE1 space. Other points of departure from BG92 involve our comparison of radio-quiet (RQ) and radio-loud (RL) sources as well as subordination of BG92 [OIII] measures (although see [35, 36]).

The principal diagnostic measures defined above can be interpreted as physical measures involving: 1) velocity dispersion of the low ionization broad line (HIL) region. It is standard to assume (and there are consistency arguments to support it) that these lines arise from a rotating Keplerian disk making FWHM (usually $H\beta$ or MgII2798) a virial estimator of BH mass. 2) R_{Fe}

involves the relative strength of low-ionization lines (LILs) that are thought to arise in the same AD structure. This ratio serves as an estimator of electron density (n_e) in the LIL gas and the high density requirement for its production supports the AD as the source of the line emission. 3) Γ_{soft} measures the strength of a (thermal) soft X-ray photon index. This is thought to be correlated with the accretion rate. 4) The CIV shift parameter measures the amplitude of systematic radial motions in the high ionization line (HIL) gas. It is sensitive to the amplitude and geometry of an AD wind.

Many other correlates exist especially for quasars above $z=1.0$. We focus this summary on low redshift results and the relevant diagnostic measures. Our 4DE1 parameter space immediately provided several clues about the kinematics and physical conditions in the broad line region. Note that the added dimensionality of 4DE1 compared to the stellar H-R diagram is required if for no other reason than the fact that the multiwavelength properties of a quasar are orientation dependent. This is most obvious for RL sources but ample evidence exists that it is also true for the RQ majority. Major clues coming out of 4DE1 are summarized here.

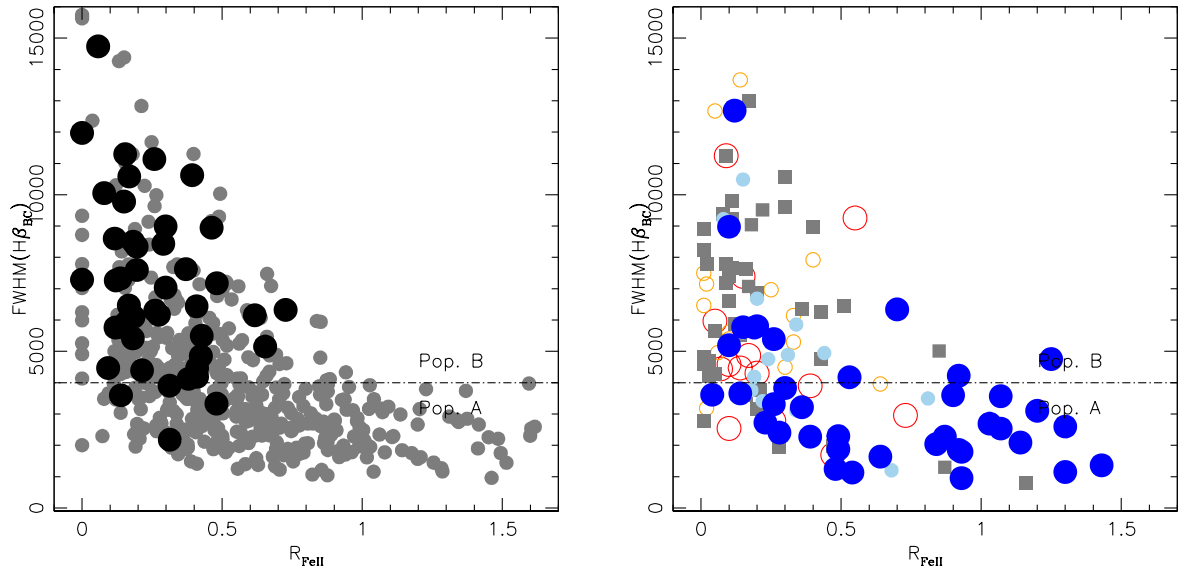


Figure 4. The 4DE1 optical plane involving the width of $H\beta$ and optical FeII strength. The horizontal line marks the boundary between population A (lower) and B (upper) sources. Left: source occupation for 470 SDSS-DR5 quasars ($z < 0.75$) with highest s/n SDSS spectra [37]. Small grey circles represent RQ sources; large black circles lobe-dominated RL sources which show a strong preference for Population B. Right: optical plane for all low z quasars with measurable HST/FOS UV spectra [38]. Different symbols represent the amplitude of the CIV 1549 blueshift at half maximum $c(\frac{1}{2})$. Large blue filled circles involve sources with the largest CIV blueshifts which strongly favor Population A. Large open circles represent sources with a large CIV redshift and grey squares those with no significant line shift [38, 23].

- Figure 4 is the clearest representation of the diversity of optical and UV spectroscopic measures in low redshift sources [33, 34]. Subsequent work suggests that the trend (i.e. source occupation) in Figure 4 (left) is driven by source Eddington ratio (proportional to the dimensionless accretion rate for constant radiative efficiency) convolved with line-of-sight orientation. M_* (stellar mass) drives the H-R diagram main sequence occupation but black hole mass plays a secondary role in 4DE1 [39, 40] in low- z samples.

Figure 4 (right panel) again shows the 4DE1 optical plane and source occupation for the 470 SDSS-DR5 quasars with highest s/n SDSS spectra. RL sources are distinguished from the RQ majority (grey dots) with symbols that reflect their radio morphology. Lobe dominated (LD—largely FRII) sources are indicated by open red circles while core-dominated (CD RL) are shown as filled blue squares. The latter are interpreted in orientation-unification scenarios as preferentially aligned LD where the radio jets are pointed along our line of sight. Our default assumption is that the radio jets are aligned perpendicular to the broad line emitting disk. The first major result is that the majority of LD sources occupy a restricted domain relative to the RQ majority of quasars. The domain is also restricted for the CIV and Γ_{soft} measures. This may be telling us that RL quasars are a distinct quasar population with different BLR structure and kinematics. A second result involves a displacement of CD RL sources towards smaller FWHM $H\beta$ and slightly larger RFE. The green arrow in figure 1 indicates the change in median optical 4DE1 measures from LD to CD. This is consistent with the orientation-unification ideas mentioned above and was previously inferred from a correlation between FWHM $H\beta$ and radio core/lobe flux ratio [41, 37].

- The multiwavelength differences between sources at the two ends of the sequence seen in Figure 4 motivated the concept of two quasar populations (horizontal line in Figure 4 left/right marks the Population A-B boundary [37] at FWHM $H\beta=4000 \text{ km s}^{-1}$. This value (and RFE=0.5) lie very close to the values identified in a 2D K-S test maximizing the parameter space separation between RL and RQ sources. Many other differences exist between largely RQ Population A sources (below 4000 km s^{-1}) and the mixed RQ/RL population B above this FWHM boundary. Physically the FWHM $H\beta$ boundary (4000 km s^{-1}) corresponds to $L/L_{\text{Edd}} = 0.2 \pm 0.1$ for a source with black hole mass $\log M_{\text{BH}} \sim 8.0$. This boundary may represent a critical Eddington ratio where the BLR undergoes a significant change in structure/kinematics. Even if it has no profound physical significance it represents a way to separate quasars into high and low accreting samples. The lack of this kind of discrimination underlies previously mentioned difficulties with attempts at developing a model for BLR physics.
- The 4DE1 context reveals that the much discussed narrow line Seyfert 1 (NLSy1) sources are not a distinct class of quasars with unusual properties. Rather they are simply the most extreme (i.e. narrowest FWHM $H\beta$) Population A sources. All evidence points toward 4000 km s^{-1} (and not 2000 km s^{-1}) as the more significant boundary for sources with $\log L \leq 46 \text{ [erg s}^{-1}]$. The limit is expected to increase for more luminous sources because of the weak, but significant, effect of increasing BH mass [42, 43].
- Other evidence that Population A and B quasars differ includes a fundamental change in broad line profile shape near the Population A-B boundary [33, 44, 38]. The broad $H\beta$ (characteristic low ionization line at low z) profile is well fit by a symmetric Lorentzian function in most Pop. A sources. Population B sources require a double Gaussian fit including broad (FWHM $\sim 5000 \text{ km s}^{-1}$) relatively unshifted component plus a very-broad (FWHM $\sim 10000 \text{ km s}^{-1}$) and redshifted (a few thousand km s^{-1}) component. CIV1549 (characteristic high ionization line at most redshifts) shows strong profile blueshifts and blue asymmetries in Population A sources but is usually relatively symmetric and unshifted in Population B sources. This description is confirmed in median composites involving 50-250 low z sources despite the fact that individual sources show an impressive diversity in profiles shapes/shifts/asymmetries.

We think that the above results offer the key to a physical model of quasars that can unify the intriguing 4DE1 sequence and the Population A-B differences. A major advance in our understanding of quasar physics is coming soon.

5. A promising future

The Eddington ratio of a quasar is proportional to the ratio of source luminosity to BH mass. If Eddington ratio and BH mass can be derived from some distance-independent measure it would be possible to derive distance-independent quasar luminosities. Quasars are now easily detected out to $z = 4$ and those in the range $1 < z < 3 - 4$ are of greatest interest because the effect of the cosmic matter density is believed to dominate over the repulsive effect of the cosmological constant in this range. Quasars radiating close to the Eddington limit show distinct optical and UV spectral properties that can be recognized in major survey spectra – if the data is contextualized within the 4DE1 formalism. Measures of the $H\beta$ spectral range and the 1900 blend yield selection criteria involving two related ratios: (i) $\text{Al III } \lambda 1860 / \text{Si III } \lambda 1892 \geq 0.5$ and (ii) $\text{Si III } \lambda 1892 / \text{C III } \lambda 1909 \geq 1.0$. A little less than 100 sources satisfying these criteria cluster around the Eddington limit with a relatively small dispersion ≈ 0.13 dex [45]. Other 4DE1 correlated parameters related to the X-ray continuum shape have been proposed [46, 47] and may become useful with new data provided by planned space missions such as Athena or ongoing ones like nuSTAR. More than 300,000 quasars are catalogued, including the 160,000 whose spectra have been collected in the recent SDSS IV - BOSS survey [48]. The optical and UV selection criteria offer the non-negligible advantage of facilitating selection of large samples from presently available data since the frequency of quasars radiating close to $L/L_{\text{Edd}}=1$ is estimated to be at least a few percent of the unobscured population. We have shown that such quasar samples can yield independent measures of Ω_M with tight limits even if samples of just a few hundred sources are considered [49, 45].

Current issues go beyond the existence of the dark energy and focus more on its properties. The simplest model for dark energy is a cosmological constant with a fixed equation of state ($p = w\rho$, with fixed $w = -1$). However, the dark energy density may depend weakly on time, according to many proposed models of its nature [50]: a general scalar field predicts w to be negative and evolving with redshift. The strength of a quasar sample also includes the possibility to construct a Hubble diagram uniformly sampling a broad range of redshift. Extreme Eddington quasars are, at least in principle, sources suitable for testing whether the dark energy equation of state is constant or is evolving as function of redshift following selected parametric forms for $w(z)$). After 50 years, and a few failed attempts, are we on the threshold of using quasars for cosmology?

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